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Modeling & Testing of Inflatable Structures for Rapidly Deployable Port Infrastructures

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Abstract

An experimental investigation of the fluid-structure interaction of a water filled inflatable membrane structure in the near shore environment was performed in the Coastal Marine Engineering Laboratory at the United States Naval Academy. The structure of interest was a 10' x 2' x 0.75' (304.8 x 60.9 x 22.8cm) tubular bag developed at the Center for Innovation in Ship Design (CISD) at the Naval Surface Warfare Center (NSWC), Carderock Division as a proof of concept for the design of a rapidly deployable inflatable structure causeway to be used either as a ship to shore connector or a breakwater. The experiments were performed over a range of test conditions including three incident wave angles, three water depths, and a number of wave heights corresponding to various sea states. Results confirmed the previous conclusions that the bag is stable and well grounded for most operational sea conditions. Large amplitude and low frequency waves can induce significant motions of the structure, but the static and dynamic frictional coefficients between the structure and the surface in contact play a critical role in these motions. For conditions where the structure was at an angle of 45° to the incident waves, highly nonlinear wave conditions are produced which created wave over-topping and oscillatory motions of the structure.

Acknowledgements

The accomplishments of this year's work have built upon the foundation set forth by the MOSES design teams of 2007-2008, including Kent Dickens, Philip Rosen, Ben Testerman, and Brenton Mallen. The current opportunity to further understand the dynamics of the MOSES concept was offered by the National Research Enterprise Intern Program (NREIP) and the Summer Faculty Research Program which are sponsored by the Office of Naval Research. All research took place at the United States Naval Academy's Coastal Engineering Basin and was supported by the Center for Innovation in Ship Design at the Naval Surface Warfare Center Carderock Division.

The experimental team consisted of:

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Abel Medellin

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- Ben Testerman and Dr. Pat Hudson for their help with managing the process and securing resources needed by the team.
- The entire staff of the USNA Hydromechanics Laboratory for their insight and support.
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- Marty Irvine for his assistance in using the Krypton Dynamic Measuring Machine

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Introduction

The conceptual design of a rapidly deployable water filled inflatable membrane causeway was developed at the Center for Innovation in Ship Design (CISD) at the Naval Surface Warfare Center, Carderock Division (NSWCCD) (Dickens & Rosen, 2007). The requirement for such a structure was born out of the need to quickly transfer soldiers, vehicles, equipment, and supplies through the surf zone where wave motions and bottom profiles can vary from region to region and there is no existing port infrastructure. Figure 1 shows the MOSES concept design delivering wheeled and tracked vehicles from offshore to the beach. The typical deployment of such a structure begins with the unfurling of the bag from a ship or barge off the shore. Water is pumped in to inflate the bag and an overpressure is applied by having a column of water above the waterline. With the additional pressure head, the structure becomes semi-rigid and is well anchored to the sea floor under the weight of the additional water column. Initial proof of concept tests confirmed that the structure could support the weight of heavy vehicles and remain stationary on the sea floor in calm water.

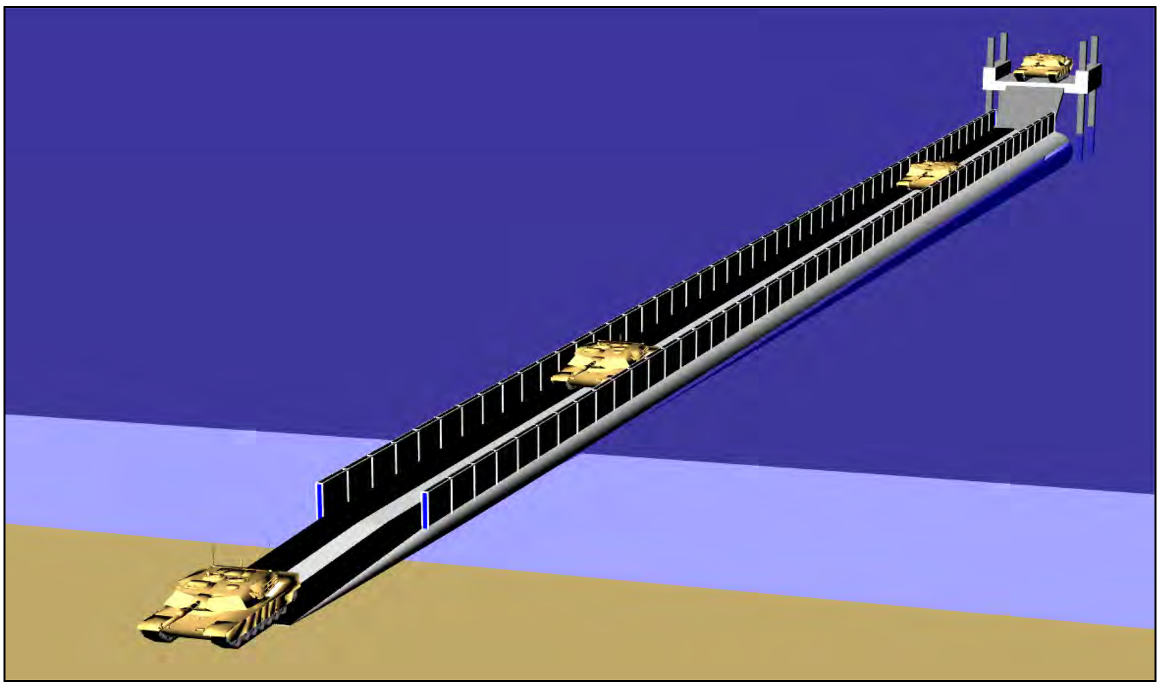

Figure 1: Concept design of rapidly deployable inflatable causeway

Following the conceptual design and proof of concept testing, a more rigorous experiment was designed to explore the dynamics of the structure in waves and on a beach slope (Testerman & Mallen, 2008). In the experiment, a revised system was constructed at 1/25th scale and tested in the 140' towing tank at NSWCCD. That facility and experimental setup used a piston wavemaker and a plywood beach added at the far end of the towing tank to model the surf zone. The structure was rigged with accelerometers to capture local and global accelerations. Unfortunately, the construction of the beach in the tank allowed it to oscillate vertically and the data was difficult to interpret after attempting to subtract the relative motions occurring between the beach and the structure. Also, testing in the 140' tank with a width of 10’ was less than ideal for modeling a near shore environment.

With the previous shortcomings in mind, a new experiment was designed to better understand the dynamics of the fluid-structure interactions of the causeway structure and an incoming wave field. The Coastal Marine Engineering Wave Basin at the United States Naval Academy, shown schematically in Figure 2, is frequently used to model nearshore environment interactions. The axes shown in the figure are the reference directions for motions measurements of the MOSES structure.

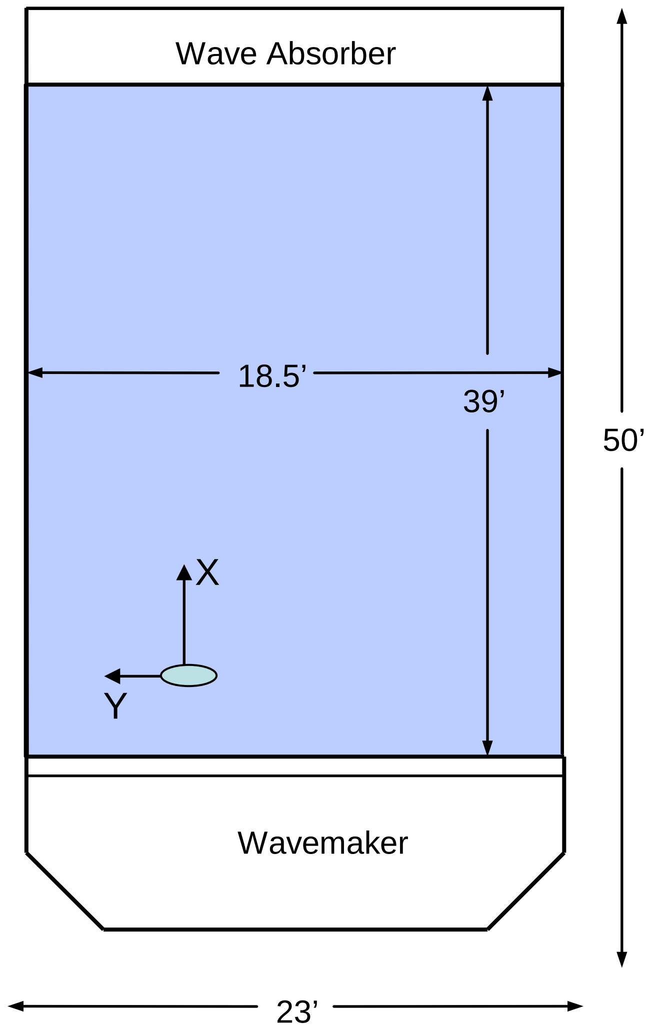

Figure 2: USNA Coastal Marine Engineering Laboratory

The principle characteristics of the basin are outlined in Table 1.

Piston Wave Maker
6” (15.24cm) stroke max.
2 Hz max.
Regular waves
Simple irregular wave spectra
Practical Water Dept Range
6”-14” (15.2-35.6cm)
Plywood Beach
Height – 9.75” (24.7cm)
Width – 96” (243.8cm)
Length – 82” (208.2cm)
Slope – 1:8.4

Table 1: Wave basin principle characteristics

Utilizing this facility, the focus of this study was on understanding the behavior of the inflated structure in waves, especially the local motions of the material, global motions of the structure with respect to the beach, and the transmissibility of wave energy through the structure when acting as a breakwater. The present experiments were conducted using the same structure from 2008 with some slight modifications.

Design of Experiment

MOSES System Model

The structure used in the experiment was designed in 2008 at the CISD at NSWC Carderock Division. It is a tubular bag constructed of woven nylon fabric coated with polyvinyl chloride (PVC). The concept design has a tapered height as it approaches the beach, but this model has a constant cross section along the length. Figure 3 highlights a two dimensional cross section in the center of the structure and provides the principle dimensions for the full scale MOSES structure.

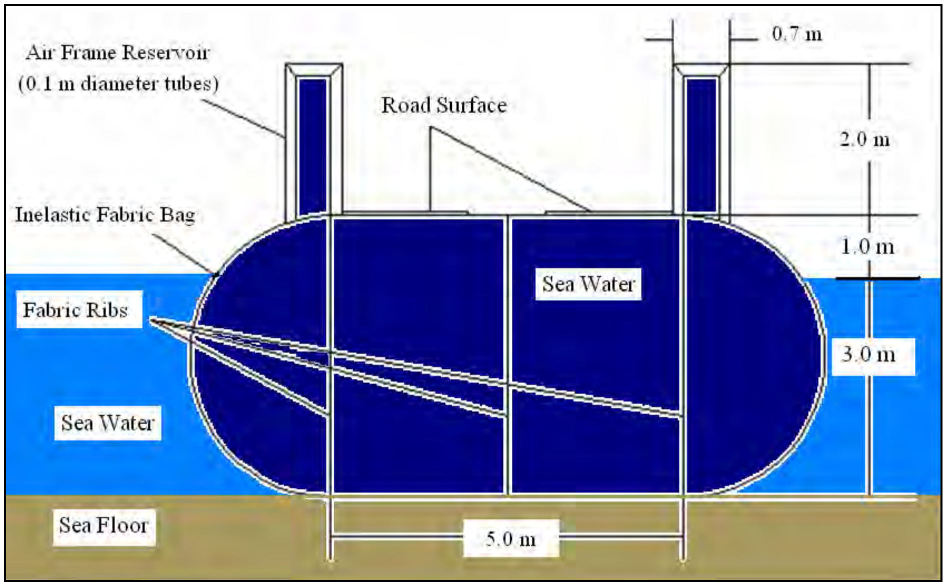

Figure 3: Graphic of a two dimensional cross-section of the MOSES system

The structure was modified from its previous implementation with the addition of a through fabric fitting for the fill hose and a constant pressure reservoir to maintain the pressure inside the structure at a constant level through the course of an experimental run. The reservoir system, which is shown in more detail in Appendix B, was comprised of a PVC cylinder with a fill hose attached to a submersible pump, another hose running to the MOSES structure's fill fitting, and an overflow spout to maintain a constant water column in the reservoir.

Environment

The waves produced in the tank during the experiment included shallow water, transformational, and deep water waves. It should also be noted that, later in the report, sea states will be used to describe wave conditions. In reality, the Sea State is a description of an open ocean environment in deep water influenced by regional winds.

The wave tank has a smooth painted concrete floor and solid PVC walls running longitudinally down the tank from the edges of the wavemaker face. A plywood beach with a 1:8.4 slope was used in a number of the test cases and was constructed with 0.5" (1.27cm) plywood and anchored down with heavy metallic rods through the base. The coefficients of friction between the MOSES structure material and both the concrete and plywood are currently unknown. However, this knowledge may be an important factor in any subsequent numerical modeling efforts.

Testing Configurations

The MOSES structure was tested in six different configurations which represent a number of the potential real world deployment scenarios. The six configurations can be split into two categories; causeway tests and breakwater tests. The causeway tests model the structure being used to deliver vehicles through the surf zone and onto the beach. The plywood beach was used in each of these runs and the model was oriented at 0°, 45°, and 90° to the incident waves for a range of wave heights and water depths. The specific values of wave parameters are found in Appendix C.

The second set of tests was carried out to test the performance of a MOSES type inflatable structure for utilization as a breakwater to provide calm water downstream for the landing of amphibious vehicles and deployment of port infrastructures. In these runs the MOSES structure was placed in the tank with 6” (15.2cm) of water depth without the beach and the model was oriented at 0°, 45°, and 90° to the incident waves for a range of wave heights.

All of the test configurations are documented photographically in Appendix B.

Instrumentation

The data acquisition and instrumentation equipment used in the experiment was chosen to best achieve the initial objectives of the project while conforming to the limitations of time and available resources. Figure 4 shows a photographic view looking upstream in the basin at the beach, model, wave probes, motion tracking LEDs, and the bridge with Krypton motion tracking camera and data acquisition systems.

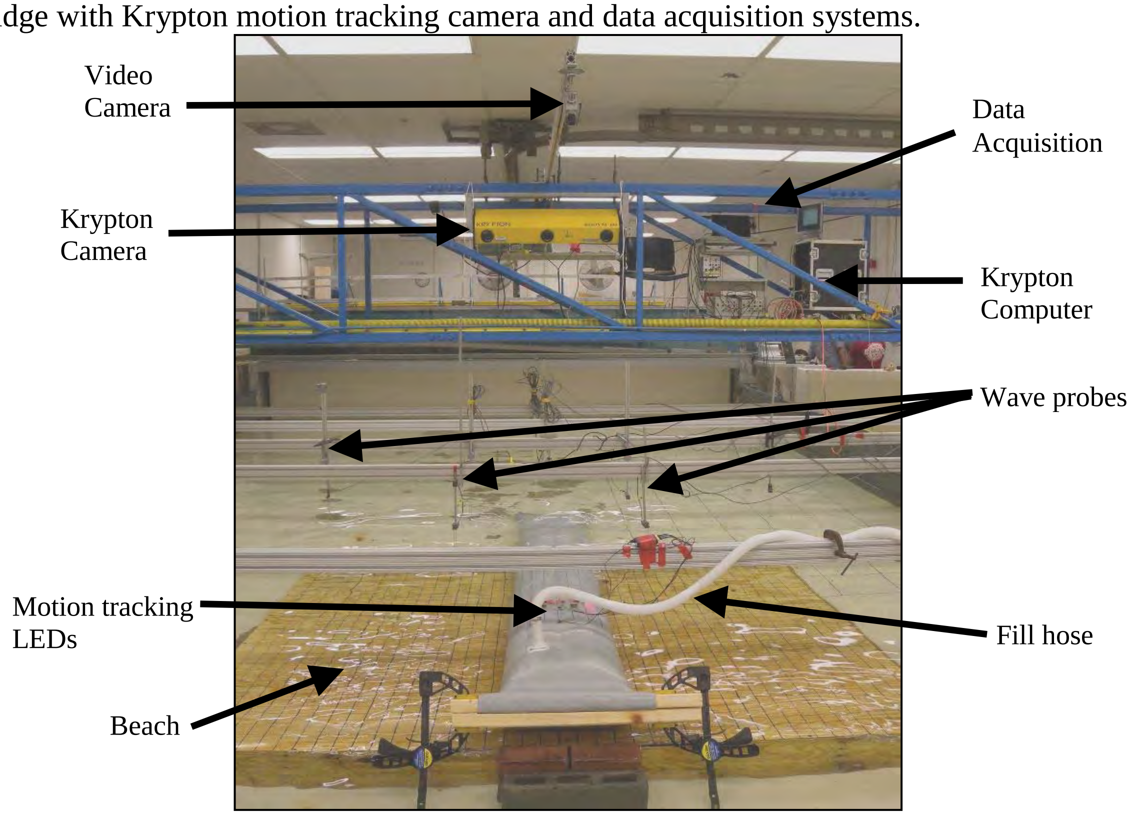

Figure 4: The experimental setup showing the key instrumentation

Two resistance wave probes were placed upstream of the structure throughout all runs to measure and record the incident wave elevation time history. Six additional wave probes were placed at various locations around the model to measure and record diffraction, reflection, and transmissibility of waves around and through the model.

The wave probe signals were sent through a signal conditioner/amplifier and then through a National Instruments USB data acquisition (DAQ) card. Each DAQ card has eight analog channels and eight digital channels. Two DAQ cards were required when using eight wave probes because the differential input of the resistance wave probe signal required a pair of analog channels per wave probe. Additionally, one DAQ card utilized a digital channel to synchronize the two DAQ's for data recording and to trigger a light emitting diode (LED) in the camera view for synchronizing the video recording with data recording. The signals were then read into a MATLAB program to analyze the data immediately after each test run and plot the wave elevation time histories.

To understand the global motions of the model in the wave basin, a series of fixed grids were drawn. One was drawn on the plywood beach with two-inch increments and the second was drawn onto the model's upper surface also with two-inch increments. These grids help to enhance observation of the model's movement during a given run for a qualitative analysis of the dynamic behavior. With two fixed camera angles, the movements of the model could clearly be inferred from the relative position of grid lines before and after each run. One camera was mounted in the x-y plane looking down at the model and the second camera was mounted in the x-z plane looking downstream in the basin at the model.

In order to gather a more quantitative perspective on the global motions of the model, a Krypton Dynamic Measuring Machine (DMM) belonging to the USNA Hydro Lab was mounted on the bridge spanning the wave basin. The Krypton DMM is a sophisticated set of three video cameras which can track the motion in six degrees of freedom for multiple infrared LEDs . The system currently requires LEDs to be above water for accurate measurements. A mounting plate with three IR LEDs was placed on the model above the waterline on the top surface. This LED mount is shown in Appendix B. All of the instrumentation is highlighted in Appendix C.

Experimental Procedure

The procedure for the MOSES model test was systematic and repeated for each run. Video, wave probe data, and displacement data were synchronized. Prior to each run the input to the wavemaker control and the video recording label are updated in accordance with the test matrix. The video recorder was started three seconds prior to triggering the wavemaker, data acquisition system, and the LED position tracking system. Data collection was marked by the lighting of a red LED in the video frame. Upon completion of the two minute run time, the DMM and DAQ files are named and saved. The wave probe locations for each case can be confirmed in Appendix D. After the completion of each run, the tank was given ten minutes to allow the basin to return to quiescent condition.

Calibration

The wave probes were calibrated by taking voltage readings in between sets of test runs when the water level needed to be changed. The sets of tests were planned such that the tank was filled to the highest depth for testing initially and water was allowed to drain down to the next depth. The voltage of each wave probe was recorded at nine different depths overall at 0.25” (0.64cm) increments. A linear relationship between water depth and voltage was observed and recorded, and the slope and intercept were used to convert voltages to wave height.

Model Testing Results

Sea State 2 & 3 Causeway Test

The results of the causeway tests in lower sea states helped to solidify one of the central aspects of the MOSES design; the solid anchoring of the structure to the sea floor under the weight of the additional water above the still water level. From visual observation during the run along with evidence provided by the Krypton, the motions of the model were identified in general as small amplitude. The three axis motion of LED 1 as measured by the DMM is presented in Figure 5 for the 0° configuration in SS2. The motions in all directions have amplitude less than 1 mm and there is no evidence of translational (sliding) motion.

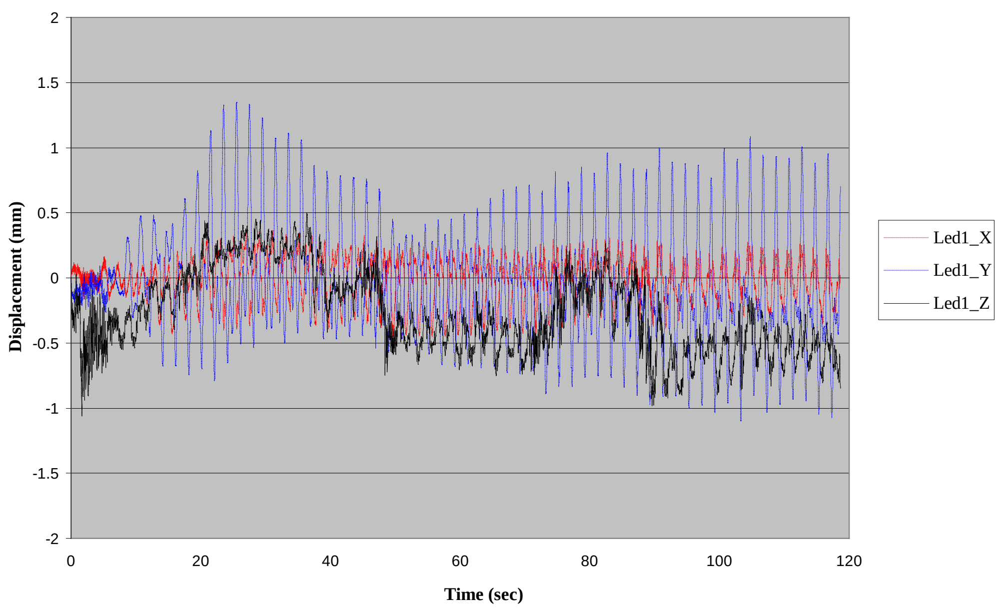

Figure 5: Krypton DMM output for LED 1 for 0° configuration with beach in SS2,

The motion of LED 1 for the 45° configuration in SS2 is presented in Figure 6 and clearly shows the increased response due to the change in exposed frontal area to the incident waves. The amplitudes of the x and y motion are relatively equal and represent a rocking type motion of the model in this type of configuration.

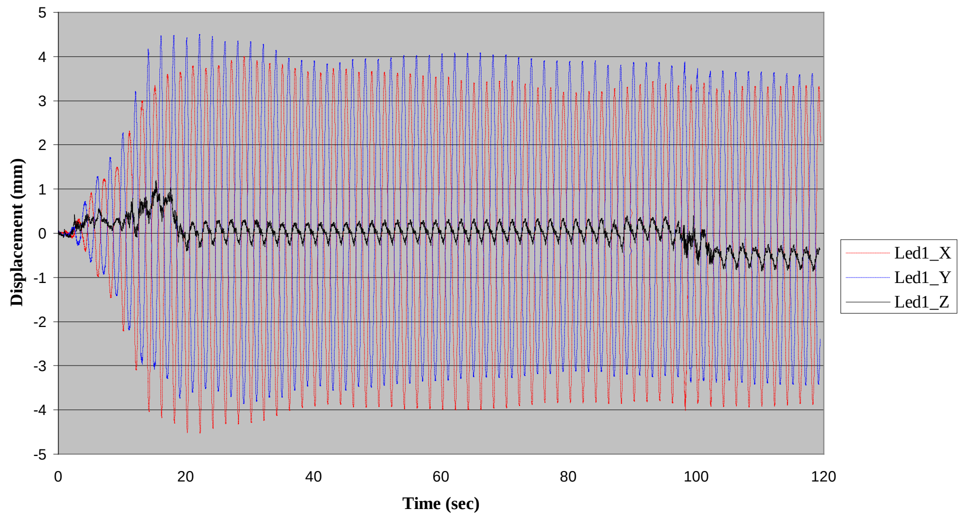

Figure 6: Krypton DMM output for LED 1 for 45° configuration with beach in SS2

In Sea State 3, in the 45° configuration, the model began to slide down the beach, i.e. downstream in the direction of the incident waves. Figure 7 shows the oscillatory type motion induced by the waves as well as a general trend of motion in the positive y-direction. An interesting observation is the decrease in motion in the x direction going to SS3 from SS2 for the 45° configuration.

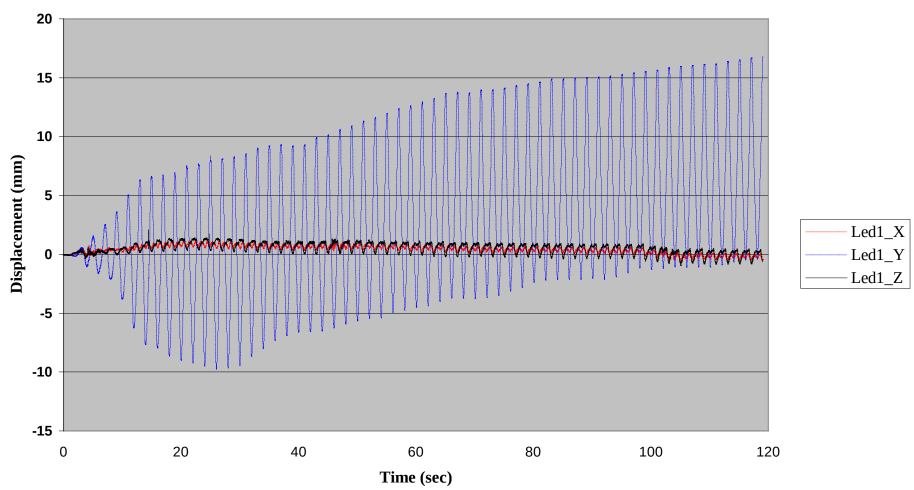

Figure 7: Krypton DMM output for LED 1 for 45° configuration with beach in SS3

Sea State 4 Causeway Test 45° and 90° Configurations

The model began to exhibit more dynamic behavior in Sea State 4, particularly in the 45° and 90° configurations. The increased area exposed to the wave forces provided the catalyst for larger amplitude oscillatory motions as well as sliding of the model along the beach. The x and y motions of LED 2 are shown in Figure 8. The x motion was in the direction on wave propagation and the y motion was down the beach. With the 45° configuration, the displacements in both directions were approximately 100 mm.

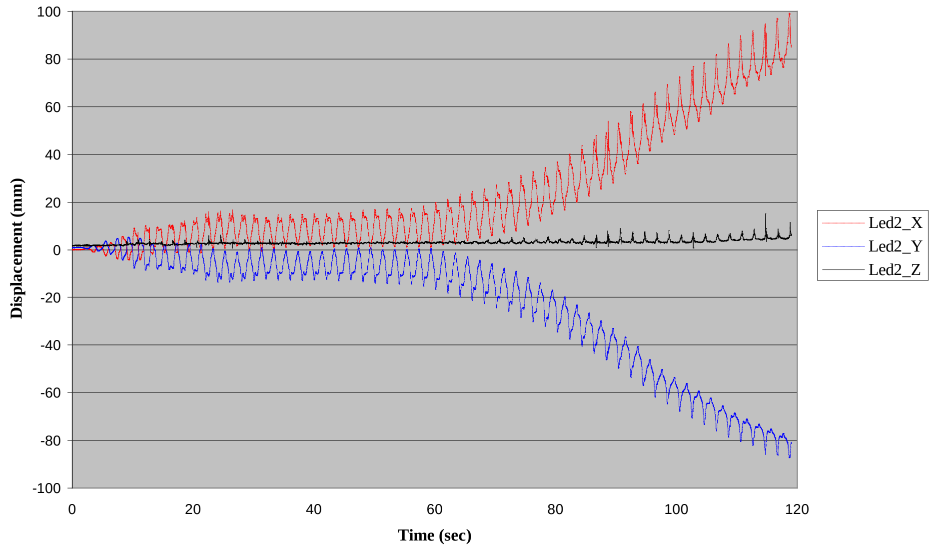

Figure 8: Krypton DMM output for LED 2 for 45° configuration with beach in SS4

The 90° configuration with the beach exhibited large motions of MOSES in the x direction but it did not appear to slide any significant distance parallel to the beach. Final displacement was 19.7" (50.0cm) in the x direction. The response of the MOSES system in waves is also present in the motions captured by LED 1 as shown in Figure 9.

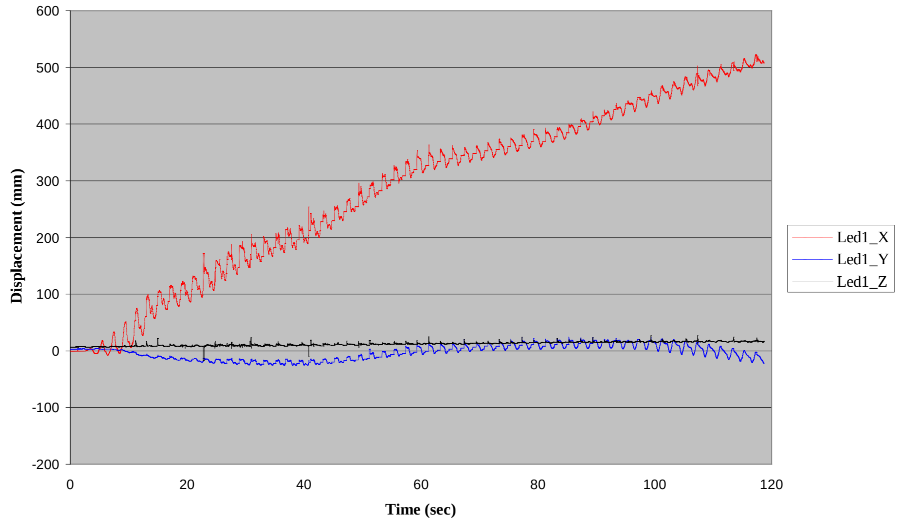

Figure 9: Krypton DMM output for LED 1 for 90° configuration with beach in SS4

Breakwater Test

The MOSES structure was tested in configurations without the beach to evaluate its alternate use as a breakwater for operation in the nearshore environment. The motions from LED 1 during a run in Sea State 4 are shown in Figure 10. The model rolled heavily as shown by the x motion data. It can also be seen that the model translated approximately 10 mm down the basin and 10 mm to the right. This was attributed to the clamping system which holds the model sealed at one end. That end may not have been grounded as effectively on the basin floor.

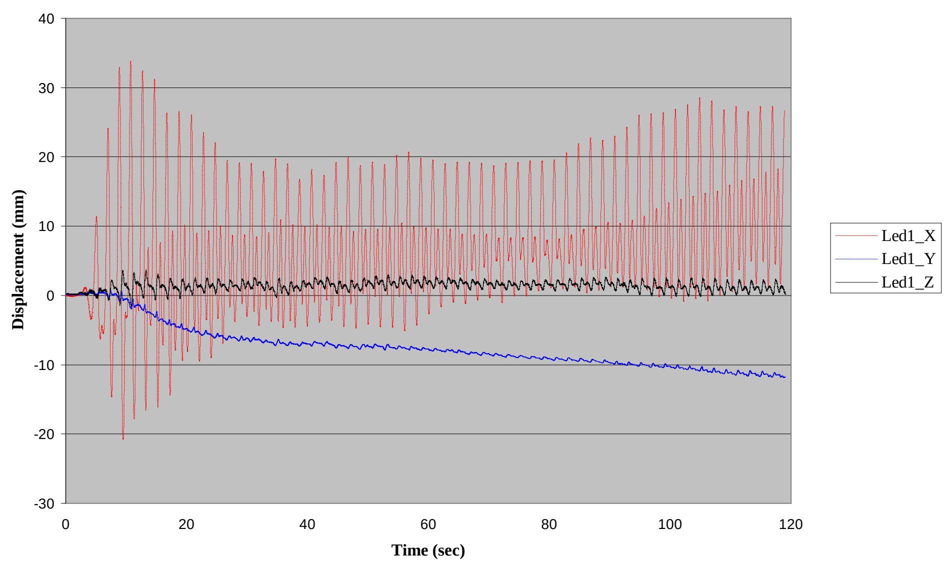

Figure 10: Krypton DMM output for LED 1 for 90° configuration (breakwater) in SS4

Unfortunately, due to probe malfunction during the breakwater testing, data on the wave field downstream of the MOSES model had to be discarded due to voltage jumps which significantly affected the ability to analyze this data and trust its accuracy.

Non-Repeatable Large Sliding Motions

Some of the test runs which exhibited large amplitude displacements were run multiple times in order to test the repeatability of the motions and gain some insight into the important effects which cause those motions. One specific case that was explored in detail was the sliding motions that occurred in the 45° causeway configuration. For a modeled Sea State 4 with 5” (12.7cm) wave height, 2 second period, and in 10” (25.4cm) of water, four individual repeats of the same run provided four final displacements of the model, 8” (20.3cm), 10” (25.4cm), 11.5” (29.2cm) and 14” (35.6cm) sideway displacements relative to the bottom edge of the beach. Three of the cases are shown below in Figure 10.

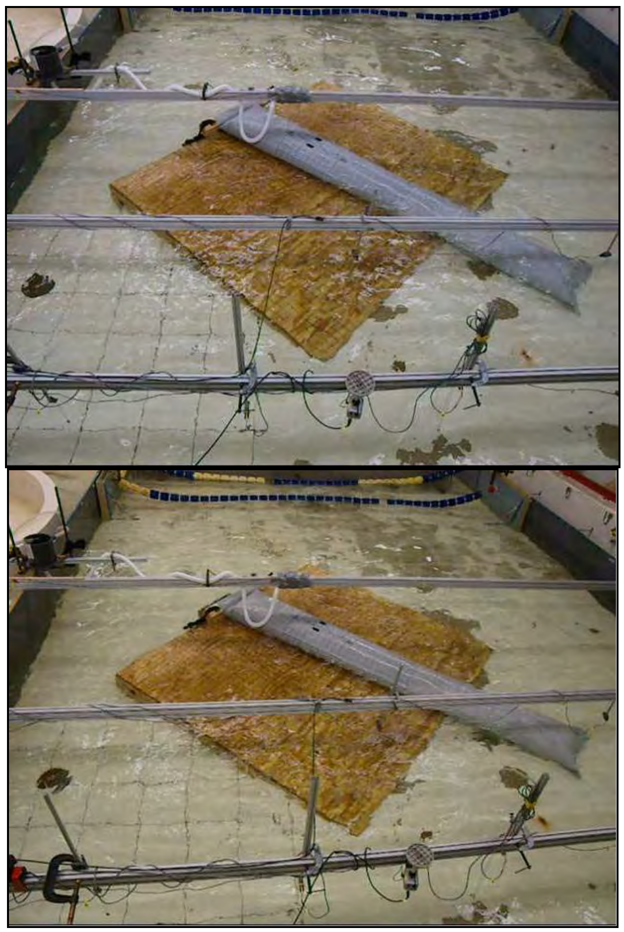

Figure 11: Non-repeatable large sliding motions in the 45° causeway configurations

A number of factors can affect the motion of the model in this configuration. On the upstream side of the model, reflected waves are sent up the beach and mixed with other waves being affected by the beach depth. The region just upstream of the model exhibits nonlinear wave fields as a result. These wave fields act on the model in a more chaotic manner and produce forces which are irregular. Figure 12 highlights these characteristically nonlinear wave forms at probe locations surrounding the upstream side of the model for this configuration. Probes 5 and 6 are directly upstream of the beach and model and probes 7 and 8 are straddling the lower section of the model where it transitions onto the basin floor from the beach.

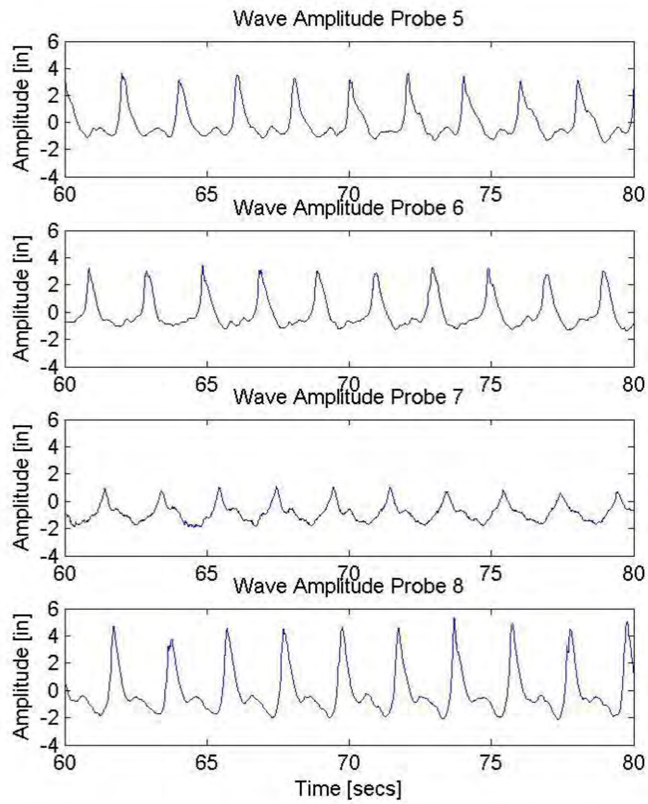

Figure 12: Wave probe data upstream of model

Large Amplitude Long Period Wave Induced Motion

Krypton DMM results for the 90° configuration with the beach in Sea State 4 were shown in Figure 8. Photographs of the initial and final positions of MOSES for this case are shown in Figure 13. These motions are excited by 4" (10.2cm) waves with a period of 2 seconds. Comparing with other cases with lesser periods, the longer period waves with large amplitude wave heights cause more significant motion of the model.

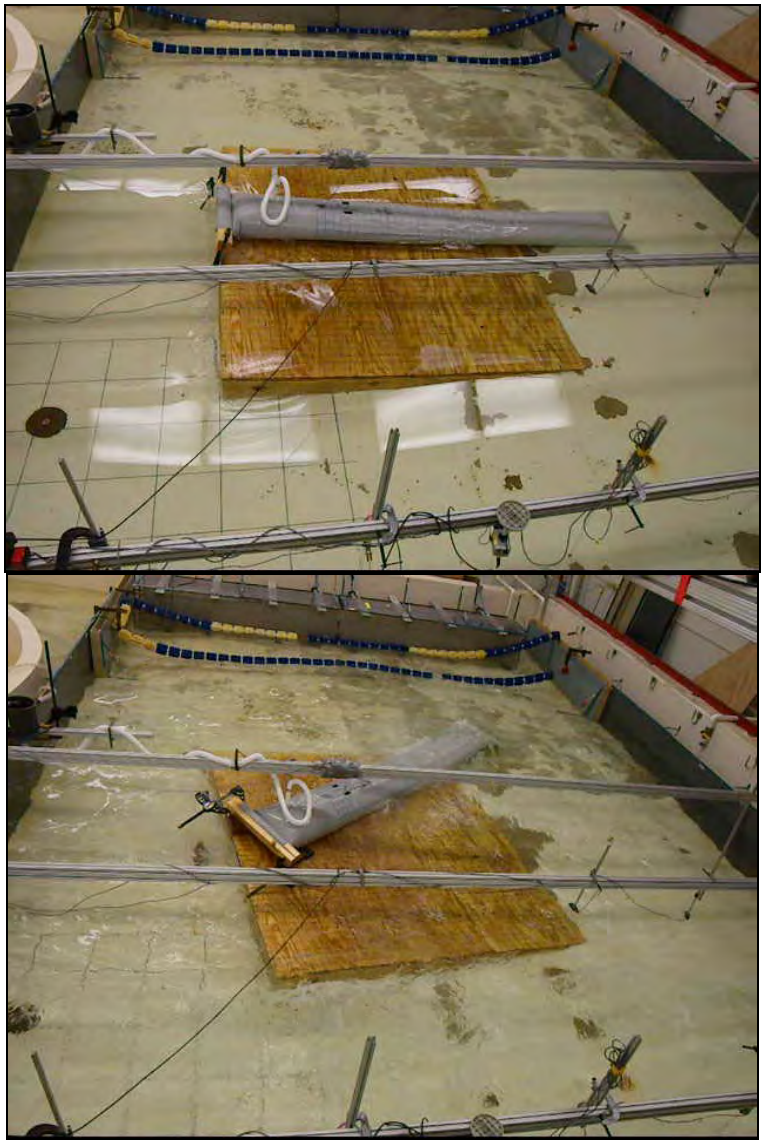

Figure 13: 90° configuration with beach in Sea State 4

Induced Rolling in 0° Configuration

One of the interesting aspects of the test cases where the model was in a 0° causeway configuration was the excitation of a rolling mode in the model. With the waves heading in the lengthwise direction of the bag, increasing the period of the waves had the ability to excite the bag in y direction in a rolling motion. This is shown in Figure 14 - Figure 16 where the wave period increases from 0.6-1.0 seconds. The figures show y motion increases significantly with the longer periods.

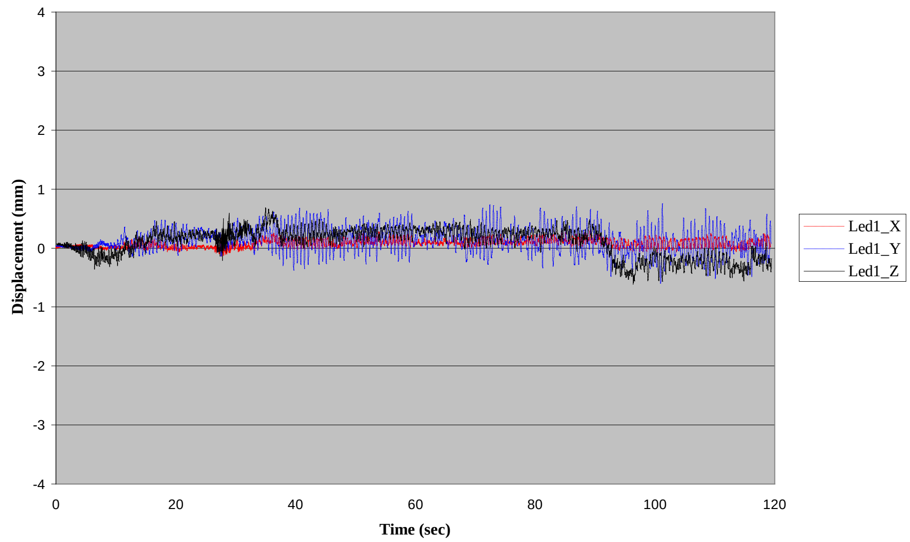

Figure 14: 0.6 second period, H = 4”

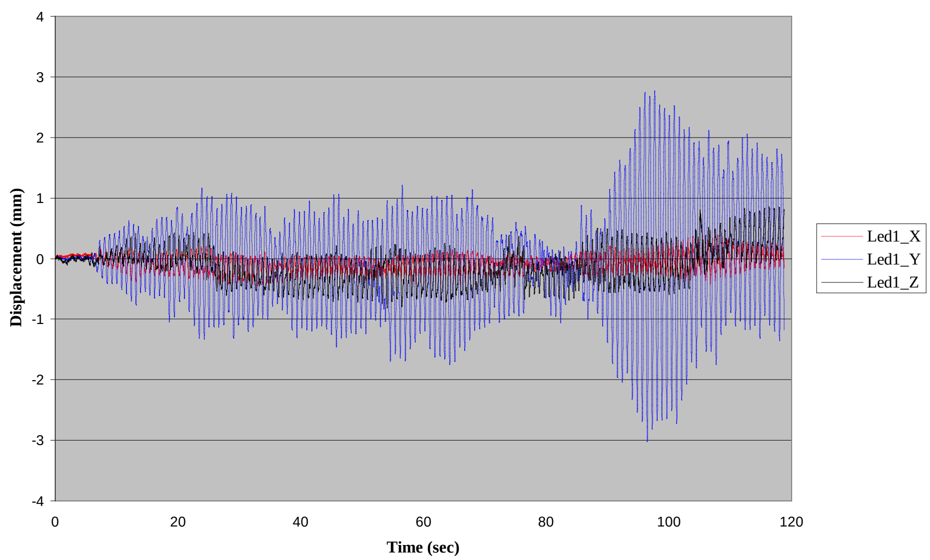

Figure 15: 0.8 second period, H = 4”

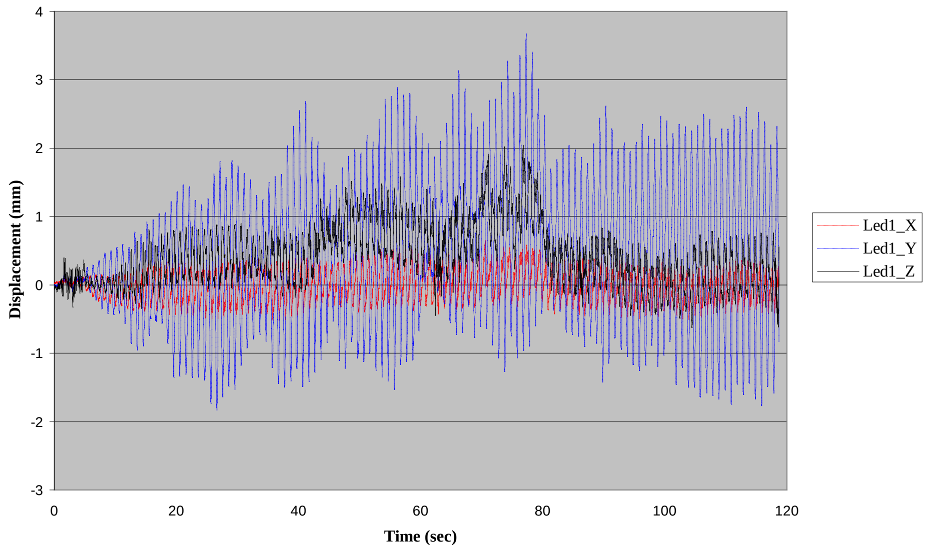

Figure 16: 1.0 second period, H = 4"

Conclusion

An experimental investigation of the fluid-structure interaction of a water-filled inflatable membrane structure in the nearshore environment was performed in the Coastal Marine Engineering Laboratory at the United States Naval Academy. The structure was tested in a causeway configuration on a sloped beach and in a breakwater configuration on a flat bottom. The experiments were performed over a range of test conditions including three orientations to the incident waves, three water depths, and a number of wave heights corresponding to various sea states up to Sea State 4. The following concluding conclusions were drawn from the study:

1. For the original (low sea states) test matrix, all the motions had small amplitudes.
2. For the causeway tests (with beach), the system was stable for all 3 configurations in Sea States 2&3. However, for Sea State 4 in 45 and 90 deg configurations, significant sliding motions occurred.
3. For the breakwater tests (no beach), the structure was stable for Sea States 2&3. For the breakwater tests at Sea States 4, sliding motion was observed in the wave direction.
4. Large amplitude and low frequency waves can (and do) induce significant motions of the structure, but the static and dynamic friction between the structure and the surface on which it lies plays a critical role in the development of these motions. Realistic frictional effects were not modeled in the tests.
5. For conditions where the structure was at an angle of 45° to the incident waves, highly nonlinear wave conditions were produced which created wave over-topping and oscillatory motions of the structure.

6. For large nonlinear motions, the experiments were not repeatable. For one set of conditions, the lateral displacement at the beach slope transition line after 60 excitation cycles varied from 8”-14” over four repeat tests.

Recommendations

Based on this experiment, provide the following recommendations for future research:

1. Submersible LEDs which can be accurately identified wet or dry by the DMM
2. Exploration of the effects of different sea floor conditions including sandy/rocky bottoms and realistic beach slope
3. Characterization of material properties/local material deflections for materials of interest
4. Better geometric scaling of MOSES in L, H, W. No taper in the length direction
5. Testing in a larger basin to match the geometry
6. Model tests of the system including static and dynamic (moving) masses to simulate movement of vehicles
7. Model tests including vertical sidewalls and pressure
8. Tests which include a variety of anchoring systems including measurement of tension forces in the mooring lines
9. More testing time in the basin
10. Use of Acoustic Doppler Velocimeter (ADV) to verify fluid velocities
11. Testing in irregular and nonlinear waves appropriate to the surf zone
12. Better characterization of coastal (near shore) wave conditions and their relationship with specified offshore sea states with a wave transformation model

References

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Appendices

Appendix A: CISD NREIP Projects – Summer 2010 Initial Briefs

Modeling & testing of Inflatable Structures for rapidly deployable port infrastructures

Introduction

Previous CISD projects such as MOSES (Summer '07 & '08) and Mulberry 21 (Summer '08) have shown potential to facilitate logistics operations through rapidly deployable, inflatable and water filled flexible structures. The purpose of this project is to explore the fluid-structure interactions of such structures in the near-shore environment. A hydro-elastic analysis of the MOSES/Mulberry concepts represents further development of inflatable structures technology in terms of concept, size, complexity, and environment. The analytic effort will explore the hydro-elastic behavior of these structures to assess feasibility and the robustness of the concepts and to identify appropriate materials, design loads, and design criteria for the concepts into the future. The analysis effort will be performed by Dr. Solomon Yim, a professor from the School of Civil and Construction Engineering at Oregon State University using state-of-the-art hydro-elastic tools. NREIP summer interns will provide support for Dr. Yim's research by conducting model tests of a scaled MOSES-like structure in a variety of wave conditions and model configurations at the United States Naval Academy's (USNA) Coastal Engineering Basin with aid from the faculty/staff at the academy and staff from Naval Surface Warfare Center Carderock Division's (NSWCCD) Center for Innovation in Ship Design (CISD). The primary purpose of the model tests is to generate data for use in validating/calibrating Dr. Yim's analytic predictions of these unique concepts. The secondary purpose is to use this data to support the potential future use of these structures and to identify further areas of development and research.

Aims

Develop an understanding for the analysis and testing of inflatable structures;
Conduct model tests in USNA Coastal Engineering Basin to provide data to validate the hydro-elastic analysis tool developed by Dr. Yim; Improve the general understanding of the performance and response of water filled inflatable structures in the marine environment.

Experimental Requirements

A proposed test matrix will be provided at the start of the project. The test matrix shall be verified for accuracy and applicability prior to the start of testing. An appropriate model shall be selected from available resources. Current options include the scaled 2008 MOSES and the USNA provided air beam structure to be filled with water. Studies should be conducted on necessary instrumentation required in order to validate the analytical tool created by Prof. Yim. Discussion with USNA Coastal Engineering Staff (through NSWCCD contact Pat Hudson) will be necessary to define available resources. The model testing shall take place in the Coastal Engineering Basin of the USNA in Annapolis, MD.

Areas of Technology Exploration

Hydro-elastic analysis of inflatable structures; Experimental techniques to collect necessary validation data for hydro-elastic analysis tools such as that developed by Dr. Yim; Model testing of water filled inflatable structures.

Constraints

Resources are currently limited to those available at USNA Coast Engineering Basin. If it is determined that additional instrumentation or equipment is needed, this will need to be discussed as early as possible in order to identify alternative items or techniques;
All rules and guidance from USNA staff/faculty must be followed in order to complete the project and promote future studies.

Approach

The team should review previous MODES and Mulberry 21 projects;
The team will review requirements and then brainstorm potential ideas. Instrumentation and test plans will be approved by CISD advisors and Dr Yim; The team will set up test sample of inflatable structure at USNA facilities, instrument according to agreed plan, and test against agreed test plan; The team will regularly liaise with Dr. Yim and provide data to him throughout the test program; Team will respond to any requested changes in the test program.

Deliverables

During the first 2 weeks, the team will produce a team project plan of actions, assignments and milestones. During the first 2 weeks, the team will review the provided testing plan and make recommendations for improvement to the plan. The team will develop and give informal intermediate presentations and a final project presentation.
All work will be documented in a CISD Project Technical Report. The final report and presentation shall be suitable for unclassified, public release. The resulting experimental data shall be analyzed and included in the final deliverables, along with a discussion of notable findings. The team will be encouraged to produce a technical paper from the final report that could be published at a professional society conference in the future.

Appendix B: Experimental Setup

Figure B- 1: MTS piston wavemaker and the USNA Coastal Engineering Lab

Figure B- 2 Constant pressure reservoir with fill hose to MOSES

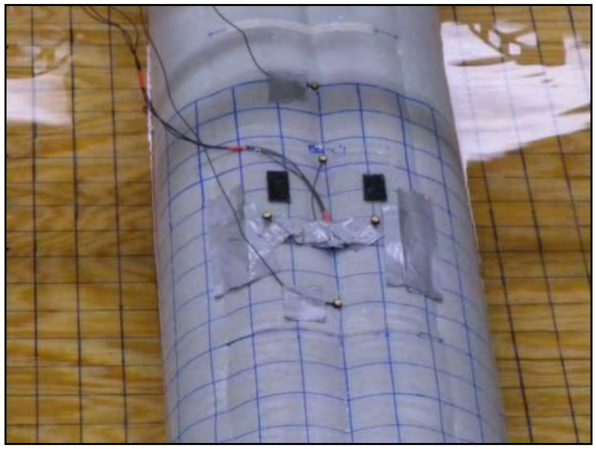


Figure B- 3: LED mounting system for Krypton DMM

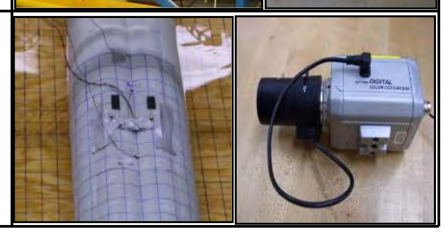
Measurement	Instrumentation	Picture
Wave Heights	Resistance wave probes, Matlab data acquisition software, and National Instruments USB DAQ cards	
Global Motion	Krypton Dynamic Measuring Machine and infrared LEDs	
General Motion	Image grid and 2 Video Recording Cameras	

Table B- 1: Instrumentation List

Appendix C: Test Matrix

Incident Wave Angle (Deg)	Wave Height (in)	Wave Period (sec)	Water Depth (in)	Number of Tests
0, 45	1, 2.5, 4	0.6, 0.8, 1.0	6, 8, 10	54

Table C- 1: Breakwater test run matrix

Incident Wave Angle (Deg)	Wave Height (in)	Sea State	Wave Period (sec)	Water Depth (in)	Number of Tests
0, 45, 90	1, 2, 4 NB 1, 2, 5 WB	2, 3, 4 2, 3, 4	2.0	6 NB 10 WB	18

Table C- 2: Causeway test run matrix (NB = no beach, WB = with beach)

Sea State	**Significant Wave Height (feet)**		**Modal Wave Period (seconds)**	
	Range	Mean	Range	Most Probable
2	0.02 - 0.11	0.07	0.80 - 3.30	1.94
3	0.11 - 0.27	0.20	1.29 - 3.80	1.94
4	0.27 - 0.55	0.42	1.57 - 3.90	2.27

Table C- 3: Scaled Sea State data at 1/15th scale

Appendix D: Test Configurations

Note: In the following images the waves propagate from the bottom of the image toward the wave absorber seen in the upper region of the image.

Causeway Test Configuration

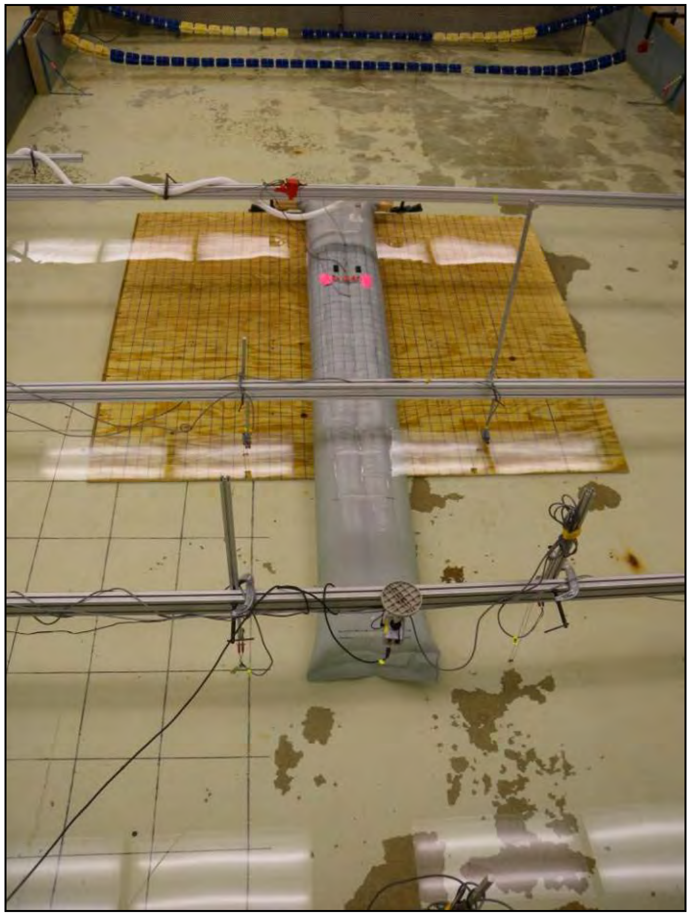


Figure D - 1: 0° causeway configurations

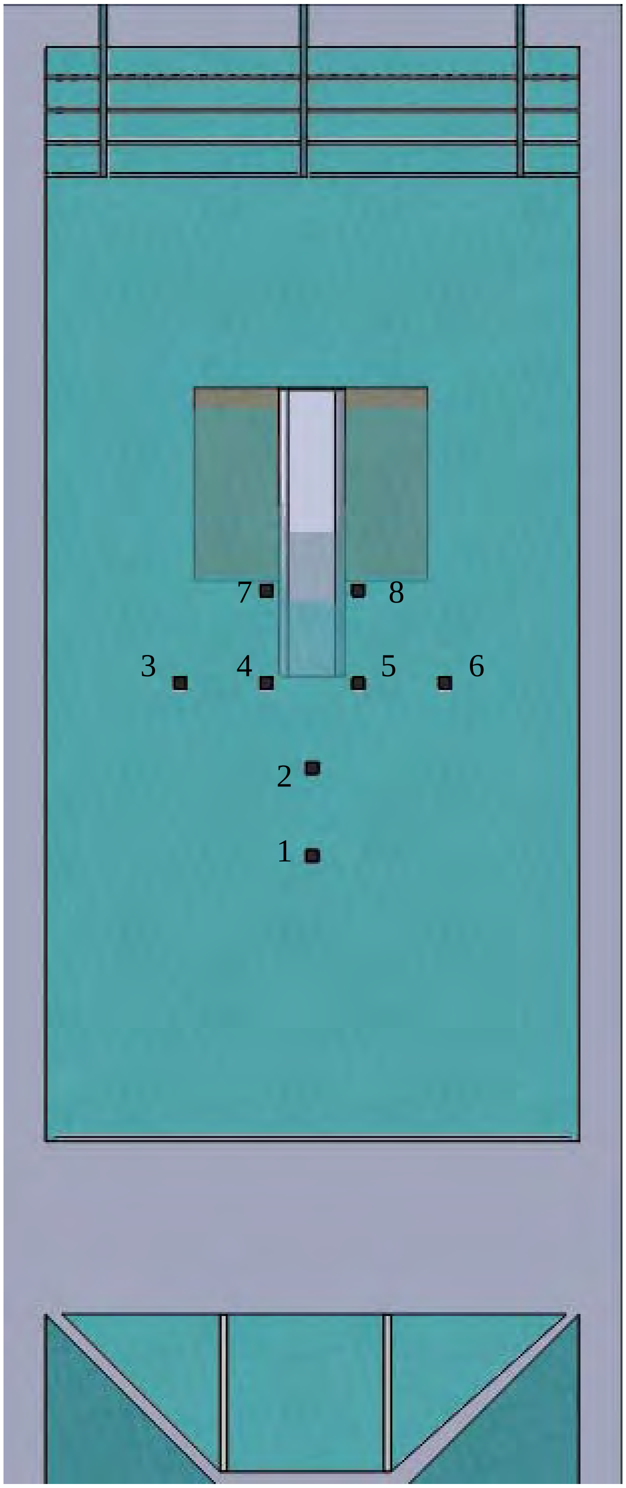


Figure D - 2: 0° causeway configuration, probe locations

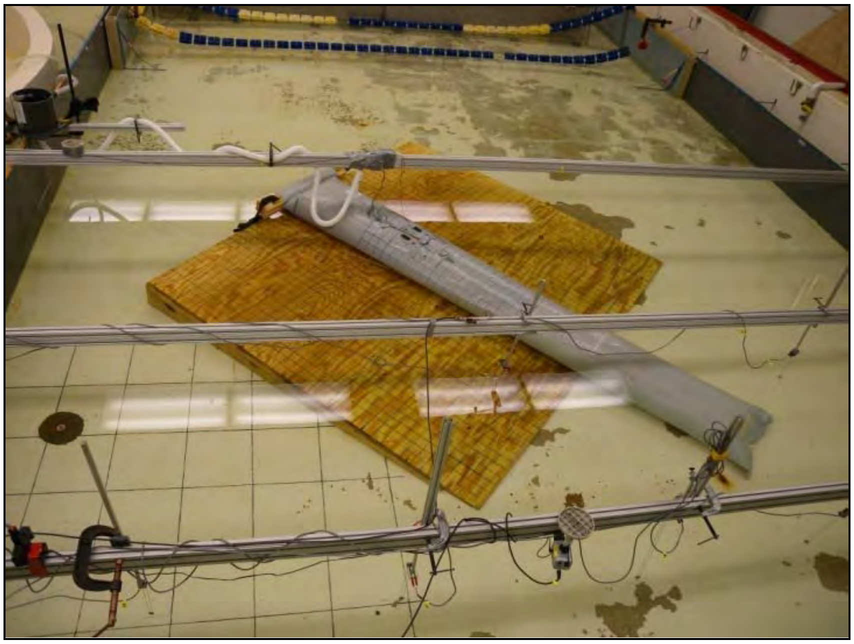


Figure D - 3: 45° causeway configuration

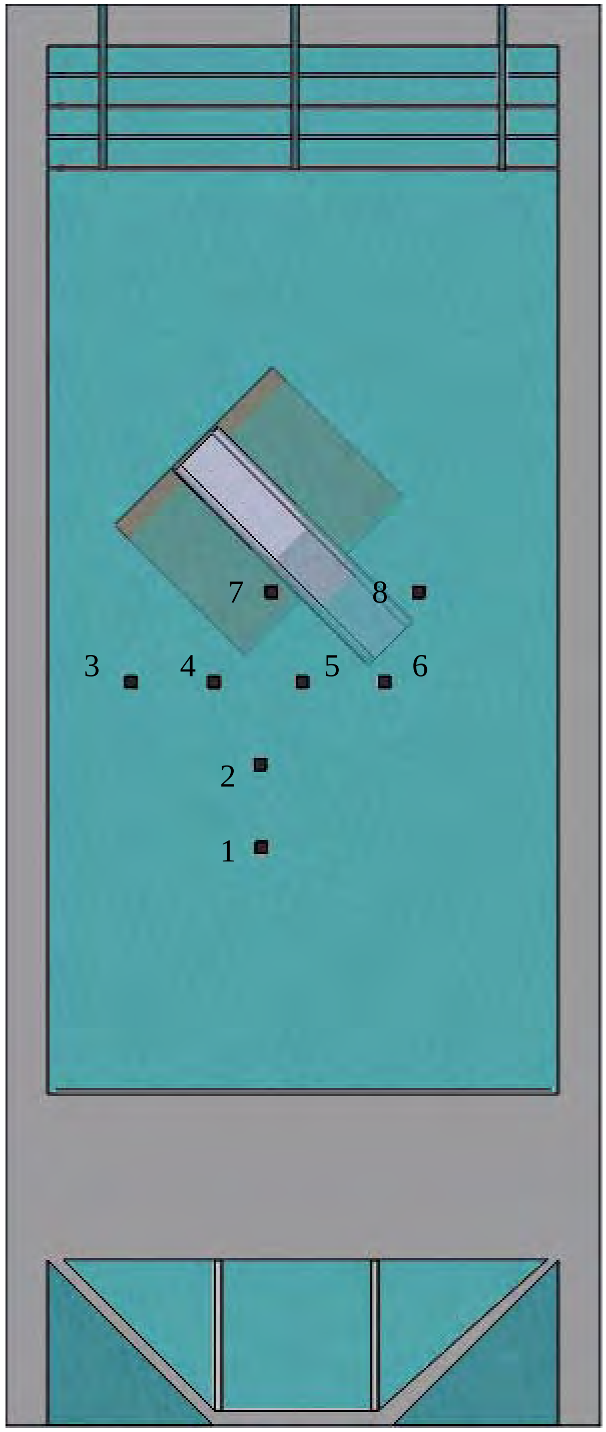


Figure D - 4: 45° causeway configuration, probe locations

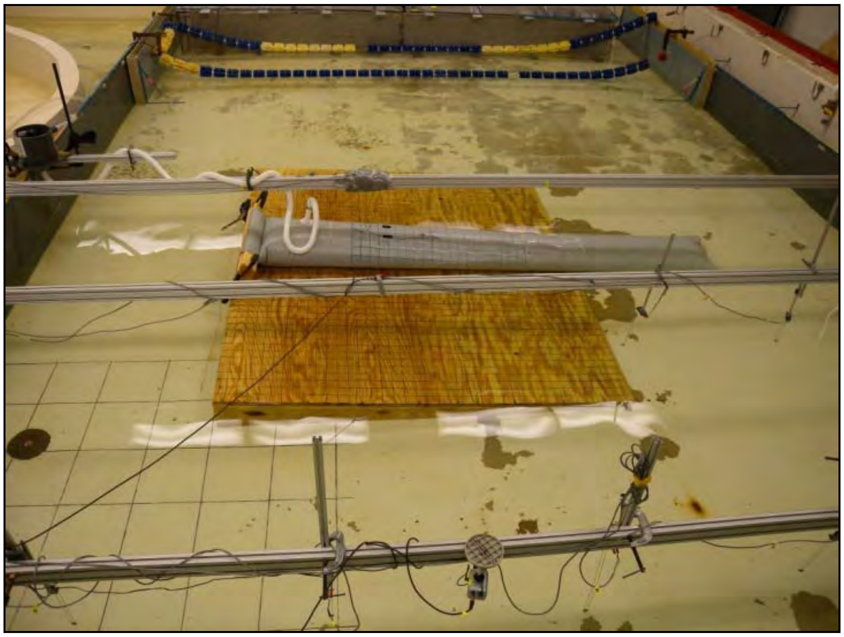


Figure D - 5: 90° causeway configuration

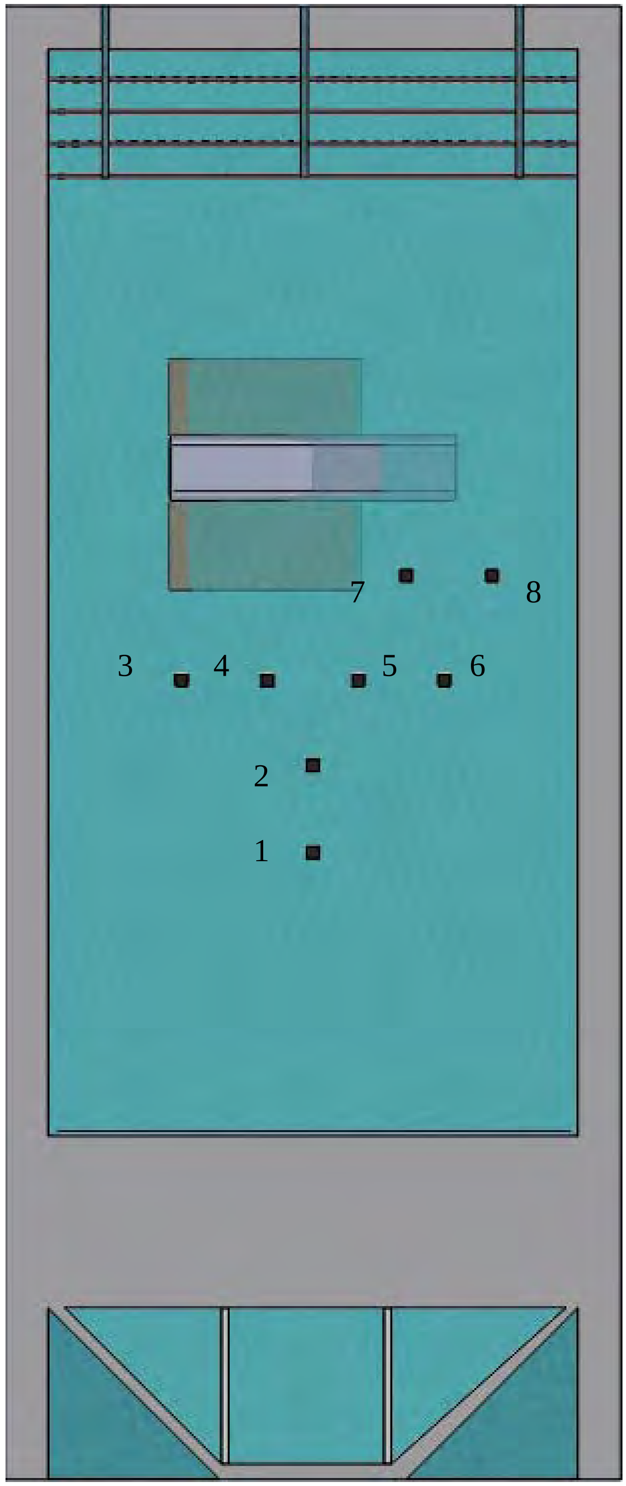


Figure D - 6: 90° causeway configuration, probe locations

Breakwater Test Configuration

Figure D - 7: 0° breakwater configuration

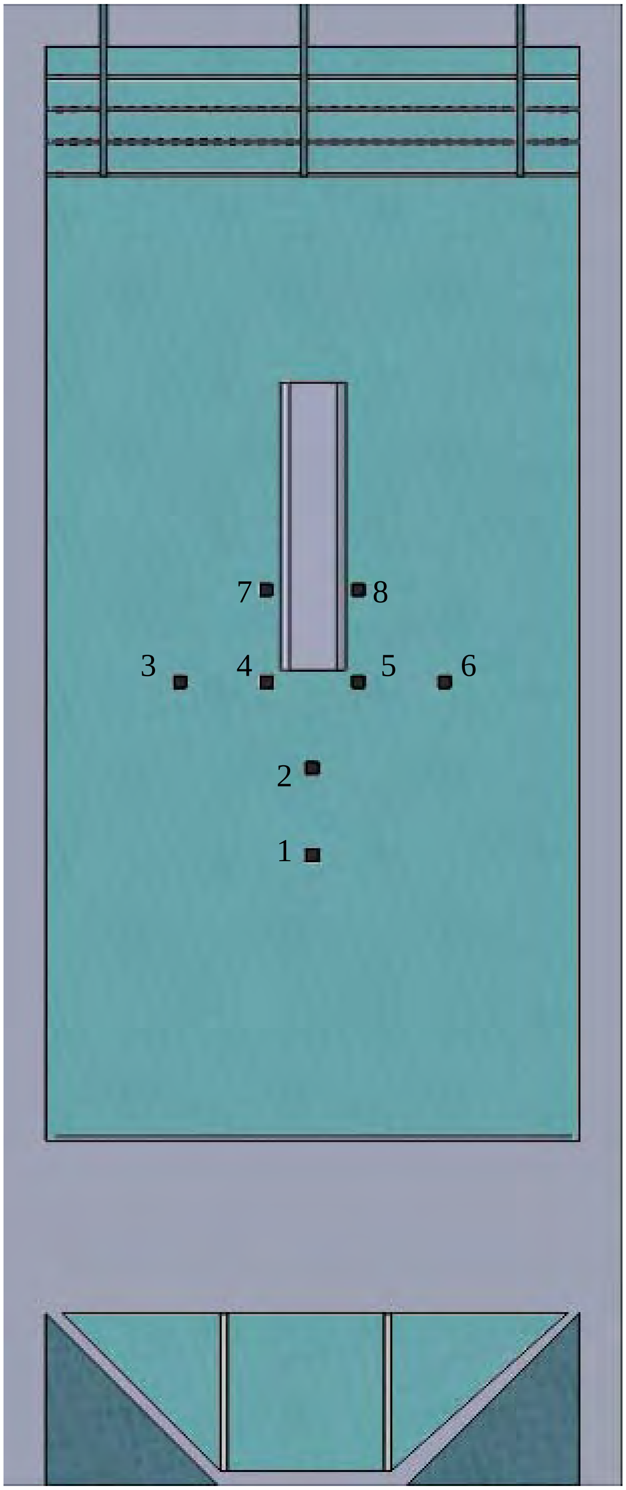


Figure D - 8: 0° breakwater configuration, probe locations

Figure D - 9: 45° breakwater configuration

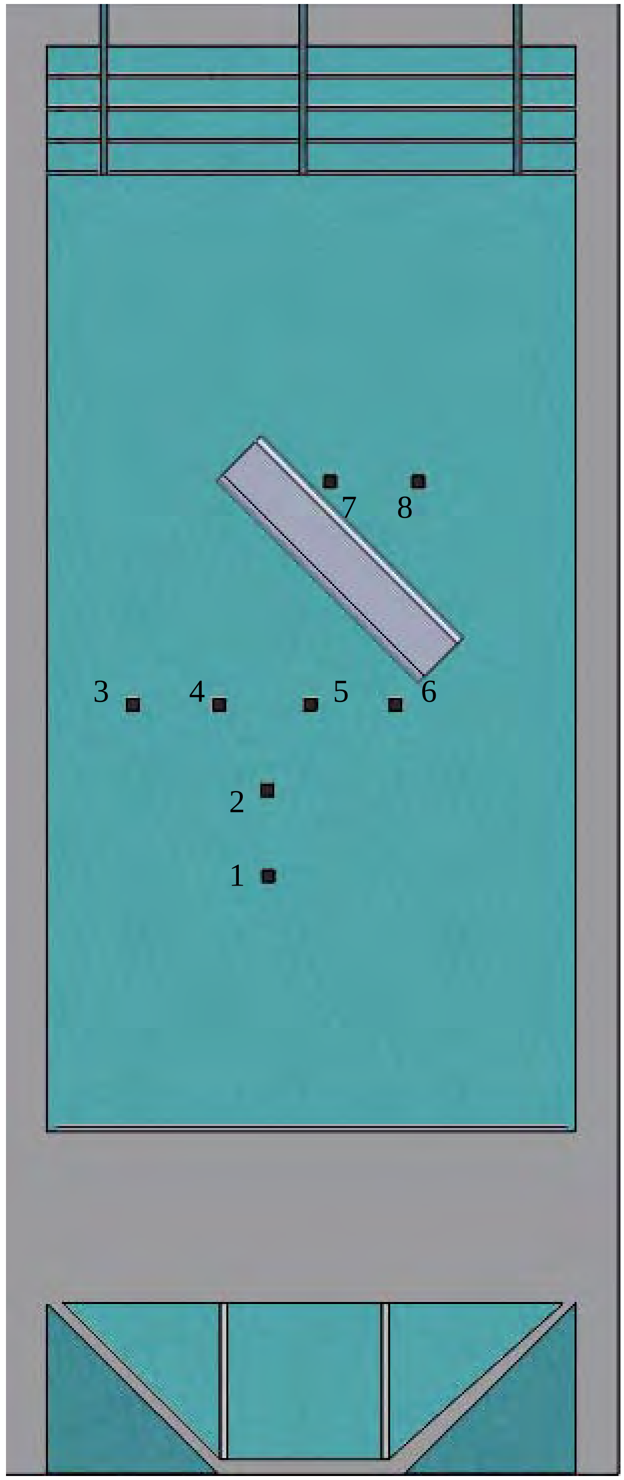


Figure D - 10: 45° breakwater configuration, probe locations

Figure D - 11: 90° breakwater configuration

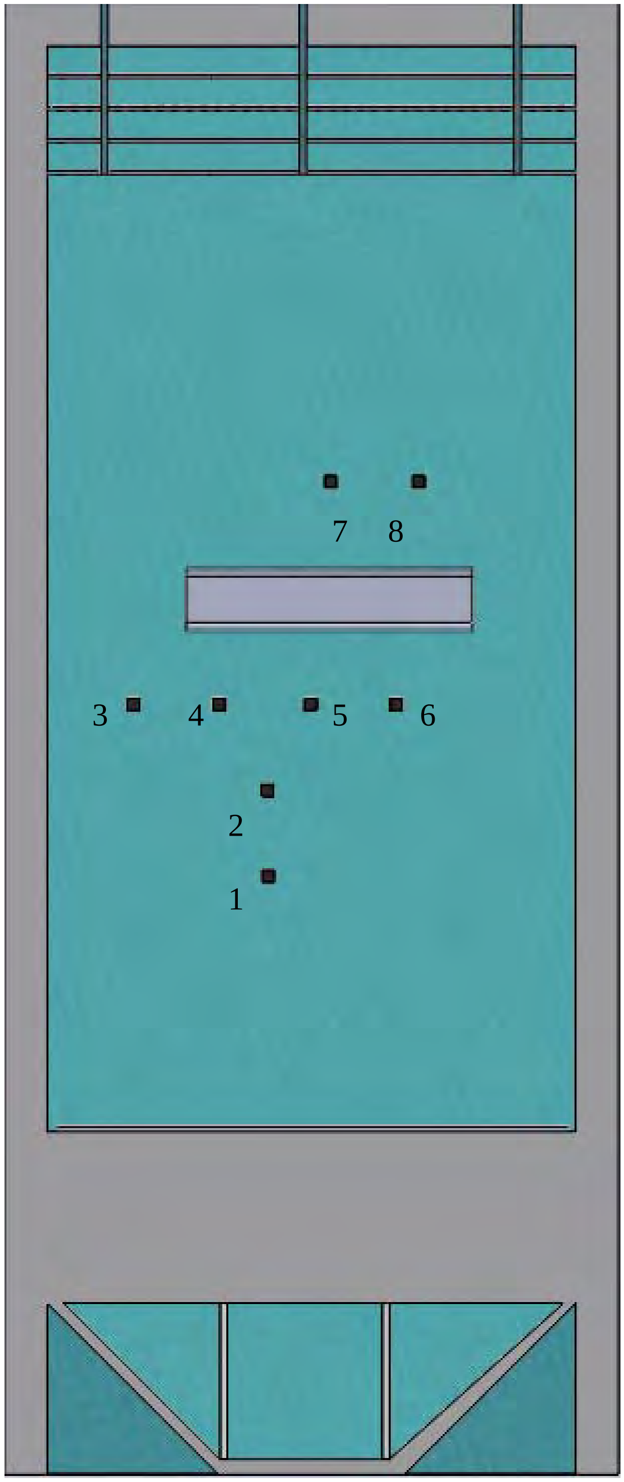


Figure D - 12: 90° breakwater configuration, probe locations